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The Argonne National Laboratory

6-7 GeV Synchrotron X-ray Source

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Introduction

In 1983 a high level technical committee was convened by the United States Department of Energy to study future needs for synchrotron-radiation based research. The committee concluded[1] that two storage ring facilities are required, a high energy facility at around 6 GeV capable of providing first harmonic undulator radiation in the x-ray region of a spectrum up to 20 keV, and a low energy facility at 1 to 2 GeV for vacuum ultraviolet light and soft x-ray up to 2 keV. For the past two years a group of scientists and engineers at the Argonne National Laboratory undertook a detailed design study of the 6-GeV facility. The Conceptual Design produced was reviewed favorably by the Department of Energy in April this year. The DOE has given this project high priority, and preconstruction research and development is underway prior to an early start on construction.

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It is impossible and, indeed, unnecessary to give a detailed description of all the components of the facility as designed and proposed. We will discuss, here, only those features which are unique and of special interest.

Ring geometry and magnet lattice

The storage ring is designed to have a large number (32) of long straight sections (6 m) with zero dispersion for accommodating insertion devices (ID) such as wigglers and undulators. The straight sections are equipped with a triplet of quadrupoles at either end to adjust the characteristics of the beam in each straight section to match the requirement of the ID. Neighboring straight sections are connected by achromatic bends. The simplest achromatic bend and one that gives the lowest emittance is the two dipole arrangement proposed by R. Chasman and G. K. Green[2]. This was adopted in the conceptual design. This lattice, however, gives a betatron phase advance per cell close to 2π, resulting in harmonics of the chromaticity sextupoles which tend to limit the dynamic aperture. In the present design these harmful harmonics are compensated by sextupoles placed in the zero dispersion locations between the tuning quadrupoles at the ends of straight sections. This critical dependence on these "harmonic sextupoles" may be eliminated or, at least, reduced by adding a third dipole to the Chasman-Green cell. This is now being studied. The general storage ring parameters are given in Table 1. Figure 1 shows the layout of one of the 32 cells of the storage ring. The amplitude and dispersion functions with the straight sections tuned alternately for undulators and wigglers are shown in Figure 2. Figure 3 shows clearly the the effect of properly tuned harmonic sextupoles in enlarging the dynamic aperture.

When the lattice is sharply tuned to give a small emittance, the beam is very sensitive to field and alignment errors. Therefore, rather complete beam position sensing and orbit correction systems are included. During initial commissioning the lattice is first detuned so that it is relatively insensitive to errors. Under this condition it is easy to inject and store a large emittance beam. The distortions are then corrected and the tuning sharpened concurrently to eventually arrive at a sharply tuned low-emittance beam with a precisely corrected orbit.

To avoid complications with trapped ions a positron beam, instead of an electron beam is stored. When proper care is taken in limiting the impedance budget of the vacuum pipe and damping all harmful higher order modes in the rf cavities, and with a good vacuum, the life time of a 100 mA beam should be well in excess of 10 hours.

Vacuum System

A good vacuum system is crucial to the high performance operation of the storage ring. A rather unique vacuum chamber cross-sectional geometry is designed. Because of the small bending angle in a dipole one can keep the synchrotron radiation from striking the outer wall of the chamber by simply adding a small slot-extension on the wall. This is shown in Figure 4. All unused radiation will, then, be absorbed on designated "crotches" as shown in Figure 5. Outgassing from the crotch is locally pumped with high speed pumps. The design of a water cooled crotch and its local pumps is shown in Figure 6. Outgassing which escapes the local pumping is conducted in and pumped by the non-evaporative Zr/Al getter strips mounted in the enlarged "antechamber" part of the slot-extension (Figure 4).

With this vacuum system very little of the synchrotron radiation outgassing from the crotches is expected to stream back to the stored positron beam. The computed pressure profiles at the beam after different amounts of beam cleaning are shown in Figure 7 for one whole cell of the ring. It is seen that after some 100 Ampere-hour of beam cleaning the average pressure is around 10^{-10} Torr.

Other component systems

Because the synchrotron radiation emerge from the storage ring only from the ends of vacuum chambers in dipoles, all magnets can, in principle, have H-type designs, except that they must be wide enough to wrap around the rather wide vacuum chamber. Higher precision and structural strength can be obtained this way than with the C-type design. This H-type design is now being studied as an alternative possibility. All magnets are designed to be capable of operating at a beam energy of 7 GeV.

The injector system consists of a 3A, 200 MeV electron linac, a tungsten positron production target, a 10 mA 450 MeV positron linac and a 1 Hz, 6 GeV synchrotron, all of conventional design. Each pulse, the synchrotron accelerates 7 beam bunches with 10^9 positrons per bunch. To fill the storage ring to 100 mA (1.7×10^{12} positrons) from a cold start will take 5.7 minutes, assuming a 70% injection efficiency. After the initial fill only subsequent top-ups are needed to keep the stored beam at full intensity.

The storage ring rf system operates at a frequency of 350.8 MHz and provides a peak voltage of 11 MV per turn and a peak power of 3 MW which is adequate for 7 GeV operation with limited insertion devices. For 6 GeV the requirements are only 8.25 MV per turn and 1.3 MW. A third-harmonic system (1052.4 MHz) is included in the design to provide additional Landau damping or bunch lengthening if required for added stability.

To provide full flexibility in the tuning and operation of the storage ring, the ID's and the beam lines, a control system with a large and expandable capacity and a full and flexible capability is designed.

Insertion devices

We make, here, some observations of the unique features of the rather high energy (6 GeV) insertion devices.

•Because of the high critical photon energy E_c(keV) = 24 B_o (B_o = peak magnetic field in tesla) at 6 GeV, the fields provided by the rare-earth-cobalt (REC) hybrid magnet configurations are generally adequate. Such fields are also sufficient to produce a deflection parameter $K = 0.934 B_o\lambda_o$ (λ_o = period length of wiggler in cm) of ~10 which provides a nearly smooth photon energy. Thus, there will rarely be need for higher field intensities.

•Because of the relatively large relativistic energy γ the horizontal opening angle of the radiation $\theta_h = \pm K/\gamma$ is small and the brightness of the radiation delivered by a wiggler is generally quite high.

•Because of the availability of long straight sections, one can consider the use of low field, hence low critical energy wigglers and still obtain rather high brightness.

•In many applications there is need for radiation linearly polarized in the vertical direction. This requires a vertical wiggler.

•The REC hybrid magnet undulators on a 6 GeV storage rirg can deliver first-harmonic radiation with energies ranging from a few hundred eV to 20 keV and on-axis brilliance ranging from 10^{18} to 10^{19} photon/sec/0.1%BW/mm^2/mrad^2.

•The energies of the first-and third-harmonic peaks from the 6 GeV undulators can be turned over ranges of between 5 and 50% by varying the magnet gap. For larger variations devices with different period length λ_o must be switched. These tuning ranges are shown in Figure 8. With higher positron beam energy these tuning lines are less steep and the same energy range can be covered by a fewer number of devices.

•At 6 GeV there will be little demand for harmonic higher than the third. Thus, the tolerances for magnet field errors are fairly high. A field error of less than 0.5% can be achieved and is quite adequate.

The parameters of a 20-keV REC hybrid undulator is given in Table 2. A design for a rigid vacuum chamber with an inner vertical aperture of 0.8 cm is shown in Figure 9.

Beam lines

An initial complement of 15 beam lines are planned for the Argonne facility. The storage ring can accommodate a total of 32 bending magnet beams and 28 ID beams. In fact, with multiple beam lines and tandem experimental stations the equivalent of ~100 beams can be realistically contemplated in the future.

The length of a beam line on the 6 GeV facility is mainly dictated by the distance from the source to the first optical element. The distance is required for the beam to spread to a sufficient large spot on the optical element so that the element can be properly cooled without damage by excessive heating. For silicon premonochromator element with liquid gallium cooling, this distance is some 30-60 m. The corresponding total length of the beam line is then some 40-80 m. Liquid Ga cooling is about 30 times more effective than water and the ultra-low vapor pressure (~10^{-11} Torr) of Ga makes its application attractive.

The power density in the beam spot on the optical elements can be further reduced by masks or apertures and/or low-energy photon absorbers which are composed of a set of very thin films of pyrolytic graphite or Be-Ag alloys. All these power reducers and optical elements are placed at small glancing angles to the beam to enlarge the area covered by the beam spot.

The front ends of all beam lines are generic in structure. A typical front end is shown in Figure 10. It consists of, from left to right after the first valve: (1) a pair of beam position monitors for feedback to the positron beam to accurately position the beam on the sample to be irradiated, (2) a pair of movable masks as absorbers, (3) a fast acting valve to protect the storage ring vacuum in case of an accidental vacuum break in the beam line. The valve is protected from the radiation by the "catastrophe mask" and the propagation of the pressure shock wave is slowed by the delay line to afford more time for the fast valve to close, (4) a second pair of movable apertures to define the beam and to reduce heating, (5) a personnel safety shutter to provide redundant safety and, finally, (6) the first optical element of the premonochromator.

Five of the 15 initial beam lines (two wiggler and three bending magnet beams) are "quick response" beams, dedicated to providing general sample-characterization capabilities to users who need quick answers to their problems. The remaining ten beams are from sources with parameters given in Table 3. The types of investigations to be accommodated by these 10 beams are visualized as follows:

1. Topography and radiography/tomography
2. Inelastic scattering with ultra-high energy resolution

3. Surface and bulk studies using high momentum resolution
4. Inelastic scattering from charge and spin
5. Advanced x-ray photoelectron spectroscopy studies
6. Small-angle scattering studies
7. General-purpose scattering for materials characterization
8. Multiple-energy anomalous-dispersion studies of proteins
9. Protein crystallography and
10. Time- and space-resolved x-ray spectroscopy.

These are, of course, only sample beams. Their functions and designs will likely undergo many modifications before the final choices are made.

In addition, a long beam for angiography is also being planned but is not included in the initial complement of beams.

Experimental area

The lengths of beam lines determine the width of the annular experimental area. To accommodate 80 m long beam lines emerging tangentially from an 800 m circumference ring requires a total width of about 33 m. This includes space allowance for the experimental "hutches", a ~6 m wide shielded tunnel for the storage ring on the inner radius side and a ~1.5 m wide clear walk way on the outer radius side. Provisions are made for extra long beams to protrude from the building. The radiography beam (total length ~350 m) and the future angiography beam are examples of extra long beams. The experimental floor is 0.3 m thick reinforced concrete and is vibration-insulated on both the inner and the outer peripheries by a 0.3 m by 3 m deep trench. The beam line is ~1.5 m above the floor. The entire experimental area is serviced by two 5-ton bridge cranes.

Laboratory and office spaces for the experimenters are provided in building modules distributed around the outside of the experimental building. They are oriented at such an angle that they interrupt the least number of long beam lines which protrude from the experimental building. The overall building and site plan is shown in Figure 11 and the cross-section of the experimental hall is shown in Figure 12.

References

1. Planning Study for Advanced National Synchrotron-Radiation Facilities, P. Eisenberger and M. L. Knotek, Chairmen (March 1984)
2. R. Chasman and G. K. Green, Brookhaven National Laboratory Report BNL50505 (1980)

Table 1 Storage Ring Parameters

Circumference	800 m
Energy	6 GeV
No. of cells	32
No. of straight sections	32
Length of straight sections	6 m
No. of dipoles	64
Dipole length	2.45 m
Dipole field	0.8 T
No. of quadrupoles	320
Maximum quadrupole gradient	17.6 T/m
Tunes ν_x, ν_y	35.27, 11.79
Transition gamma γ_t	56.4
Chromaticities ξ_x, ξ_y	-95, -36
Chromaticity sextupole strengths	4.64 m^{-2}, -3.86 m^{-2}
Maximum β_x, β_y	31 m, 27 m
Natural emittance	7.8×10^{-9} m
Transverse damping time	7.0 ms
Synchrotron damping time	3.5 ms
Revolution frequency	0.3747 MHz
Harmonic number	936
RF frequency	350.757 MHz
Peak rf voltage	10.5 MV
Natural energy spread	0.1%

Table 2 Parameters of a 20-keV REC Hybrid Undulator

Undulator period λ_o	1.6 cm
Magnet gap G	1.0 cm
Pole width	4.0 cm
Pole height	2.50 cm
Pole thickness	0.45 cm
Magnet width	4.8 cm
Magnet height	3.05 cm
Magnet thickness	0.575 cm
Pole-tip overhang	0.05 cm
Peak field on axis B_o	0.236 T
Peak K on axis	0.352
Number of periods	312
Length of undulator	5.0 m

Table 3 Parameters of Radiation Sources for Sample Beams

Sample Beam Line	Device	Magnetic Field (T)	E_c[a] (keV)	Period (cm)	Number of Periods	Peak K	Length (m)	Vertical Opening Angle (± mrad)	Horizontal Opening Angle (± mrad)	Total Power (kW)	Peak Power (kW/mrad^2)	Normal-Incidence Surface Peak Power Density (W/mm^2) at	
												30 m	40 m
1	Wiggler	1.2	28	20	10	22	2.0	0.085	1.9	6.5	16.7	18.7	10.5
2	Undulator	0.24	20	1.6	312	0.3	5.0	0.085	0.025	0.7	57.8	64.6	36.3
3	High-Brightness Vertical Wiggler	0.4	9.6	25	20	9.3	5.0	0.79	0.085	1.8	11.2	12.5	7.0
4	High-Brightness Wiggler	0.1 (1.2)	2.48 (28)	83 (20)	6 (10)	7.8 (22)	5.0 (2.0)	0.085 (0.085)	0.66 (1.9)	0.06 (6.5)	0.8 (16.7)	0.89 (18.7)	0.50 (10.5)
5	Undulator	0.16	1.6	10	50	1.5	5.0	0.085	0.128	0.29	10.9	12.1	6.8
6	Undulator	0.35	5.0	3.8	131	1.26	5.0	0.085	0.107	1.4	62.5	69.4	39.1
7	High-Brightness Wiggler	0.56	13.4	25.0	20	13.4	5.0	0.085	1.14	3.6	15.6	17.4	9.8
8	High-Brightness Wiggler	0.4	9.6	25	20	9.3	5.0	0.085	0.79	1.8	11.2	12.5	7.0
9,10	BM	0.8	19.3	-	1	-	2.45	0.085	-	7.1	0.56	0.63	0.35

[a]Refers to critical energy for the wigglers and first-harmonic energy for the undulators.

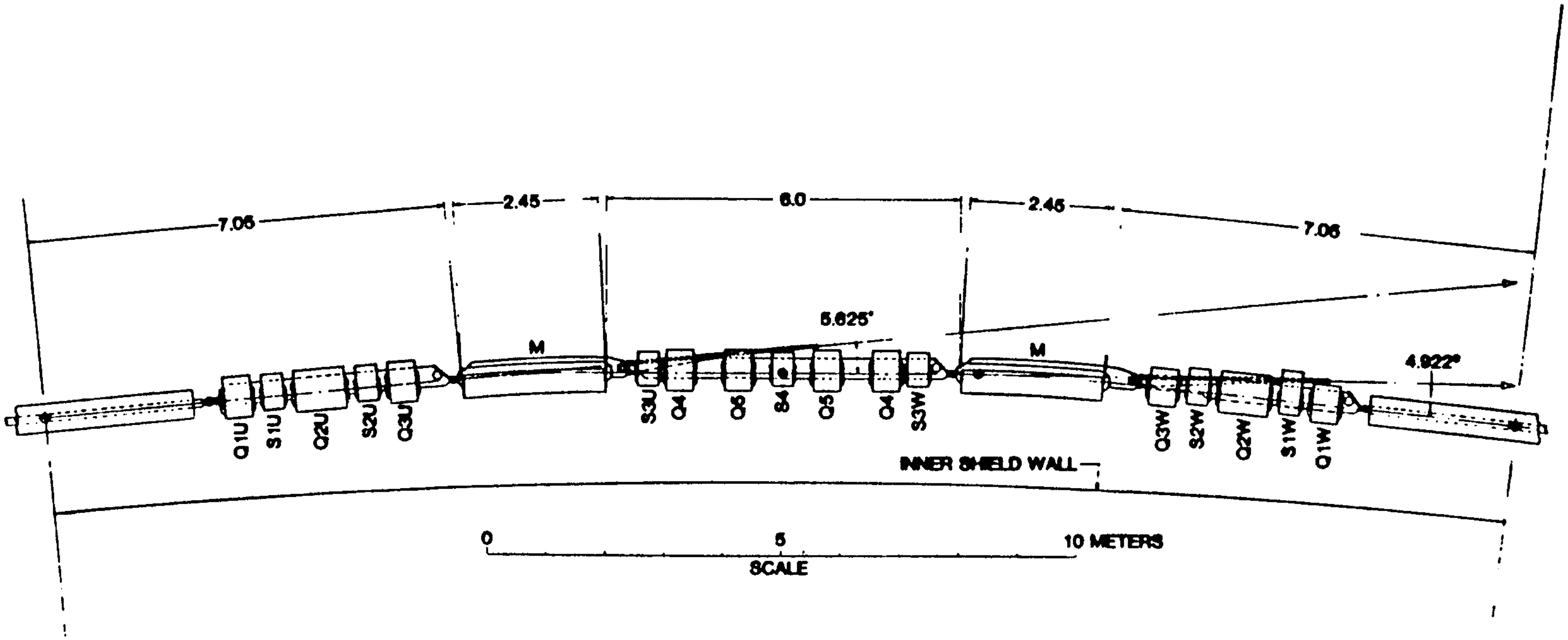


Figure 1   One cell of the storage ring

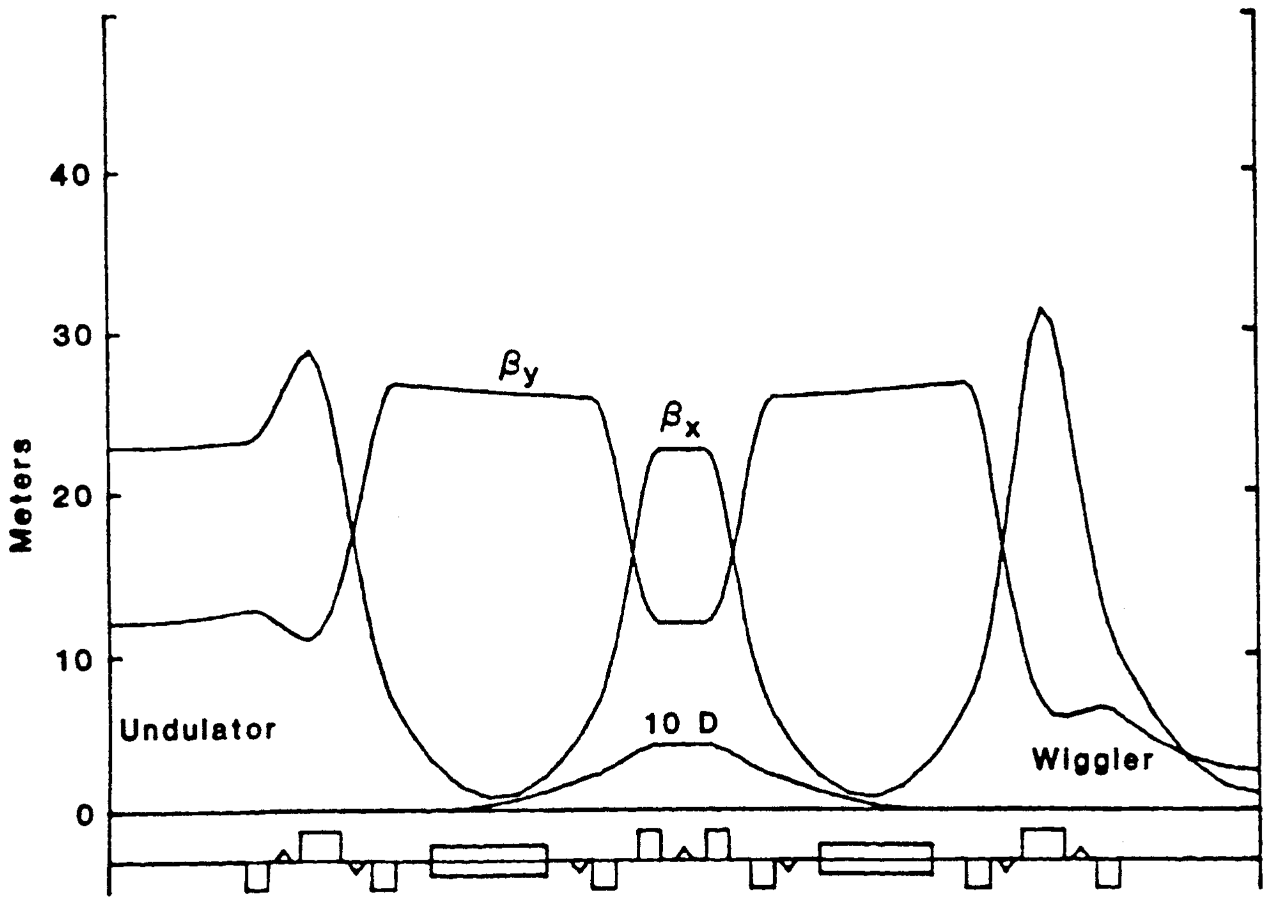


Figure 2 The amplitude (β_x, β_y) and dispersion (D) functions in an alternating undulator-wiggler lattice (reflection symmetry about either end)

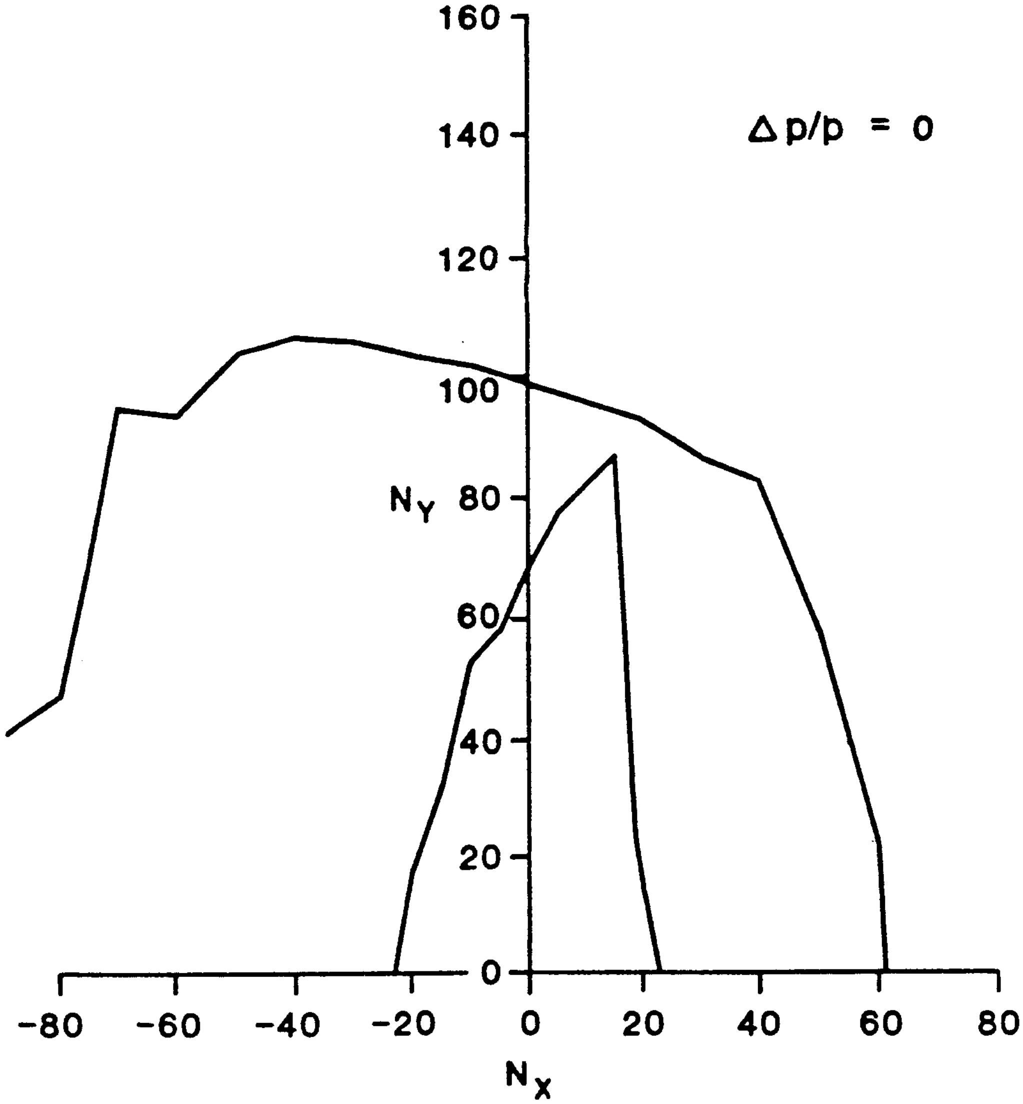
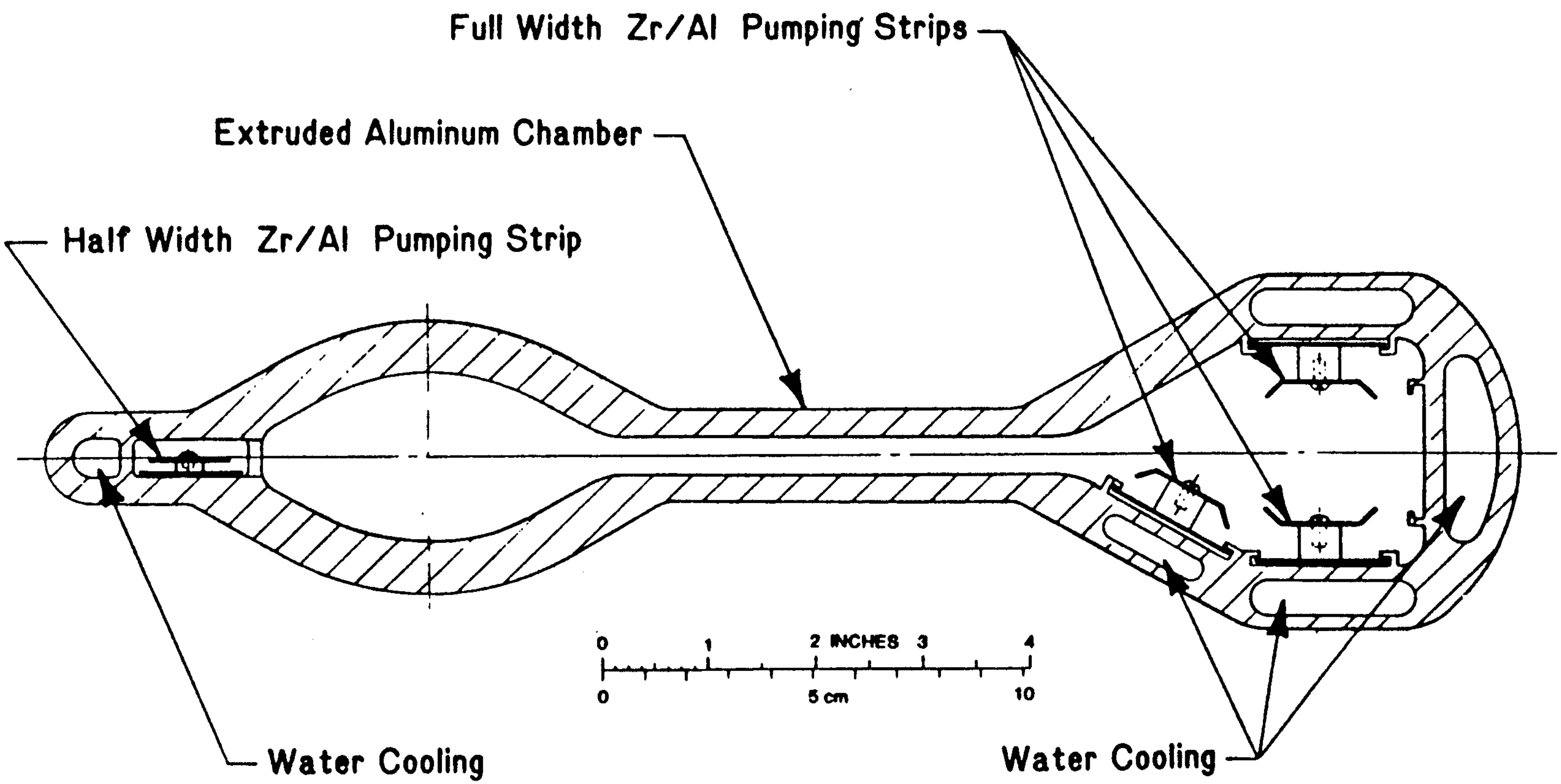


Figure 3 Dynamic aperture in units of rms beam widths σ_x and σ_y with (outer curve) and without (inner curve) compensating harmonic sextupoles



<u>Figure 4</u> Storage ring vacuum chamber cross section

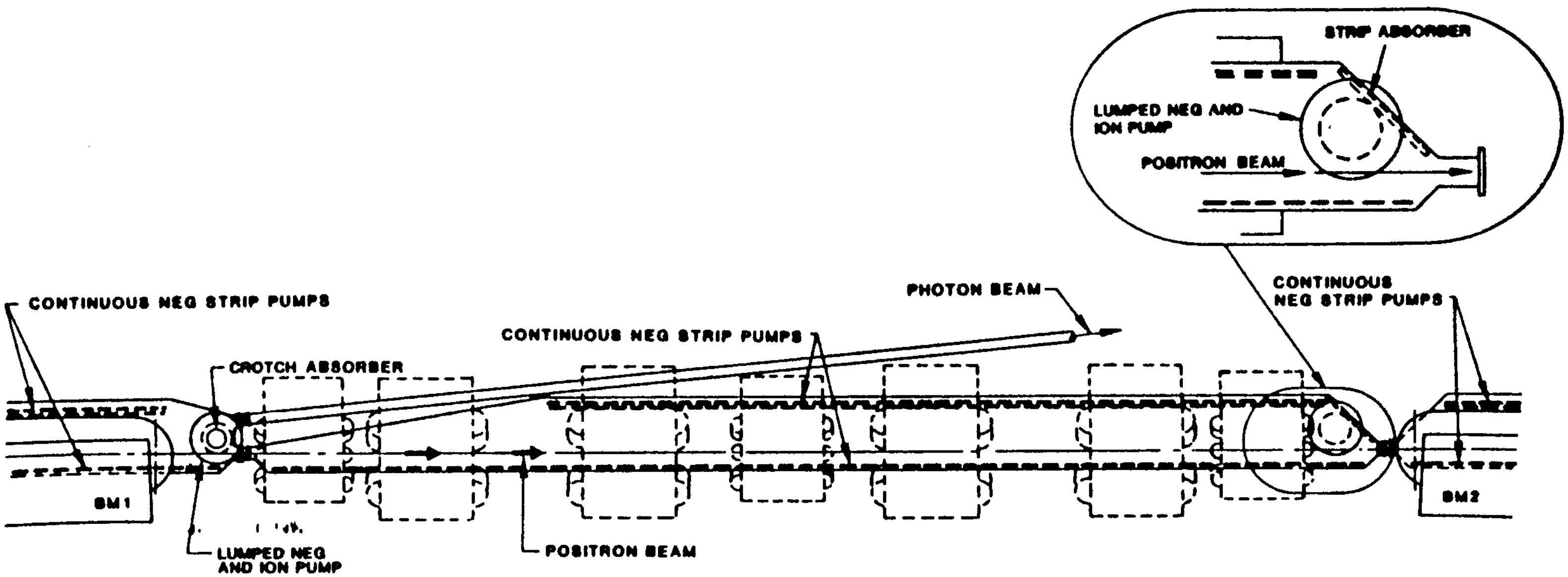


Figure 5 Plan view of a section of vacuum chamber showing the crotch absorbers

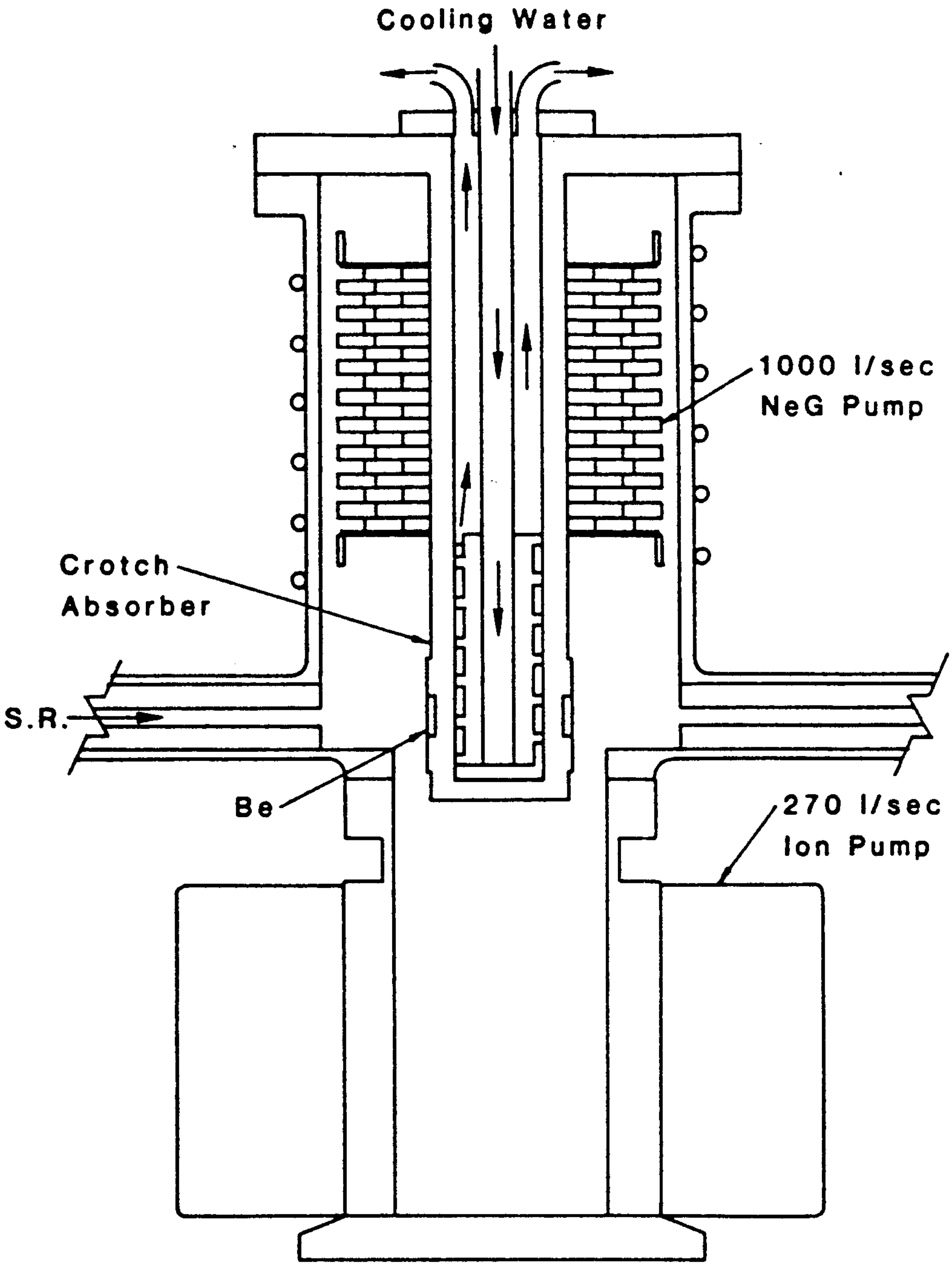


Figure 6 Cross section of crotch and local pumps

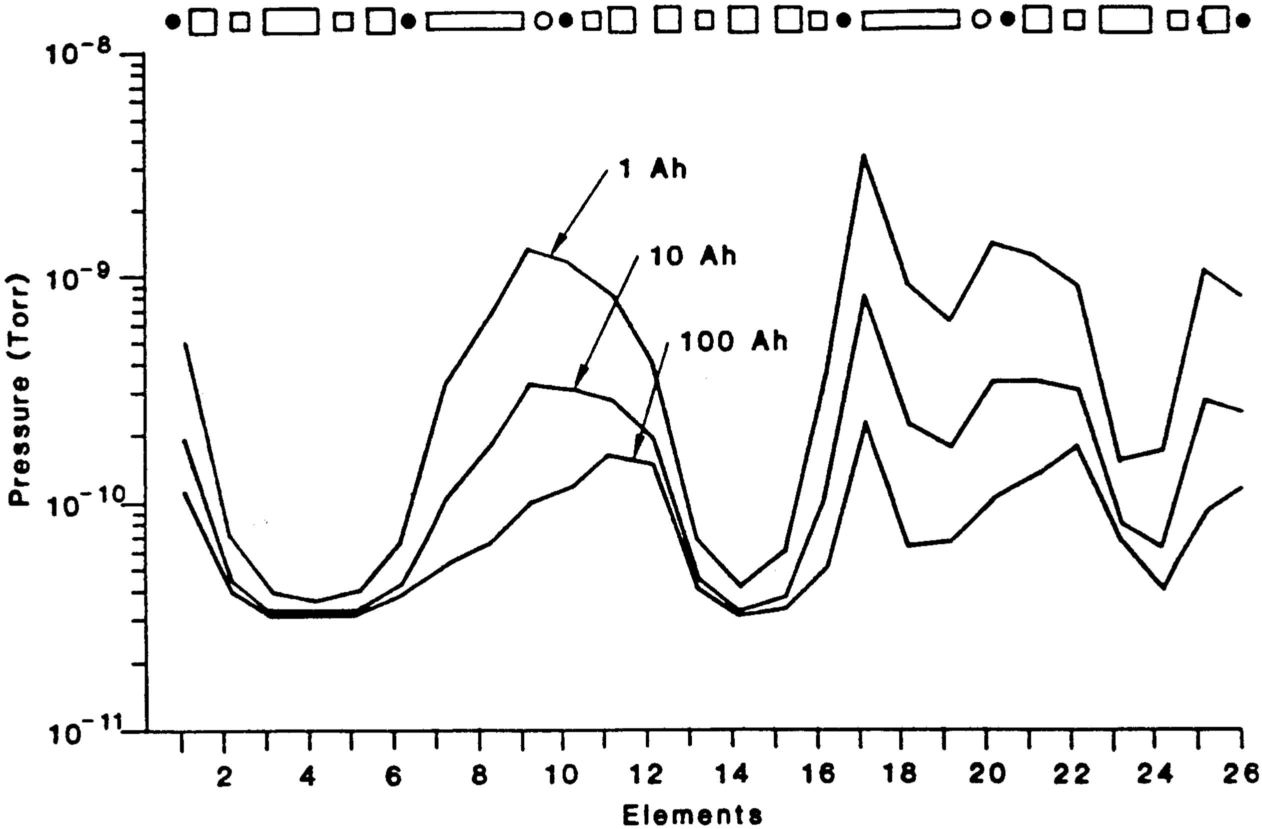


Figure 7 Pressure profiles after various amounts of beam cleaning (in ampere-hour)

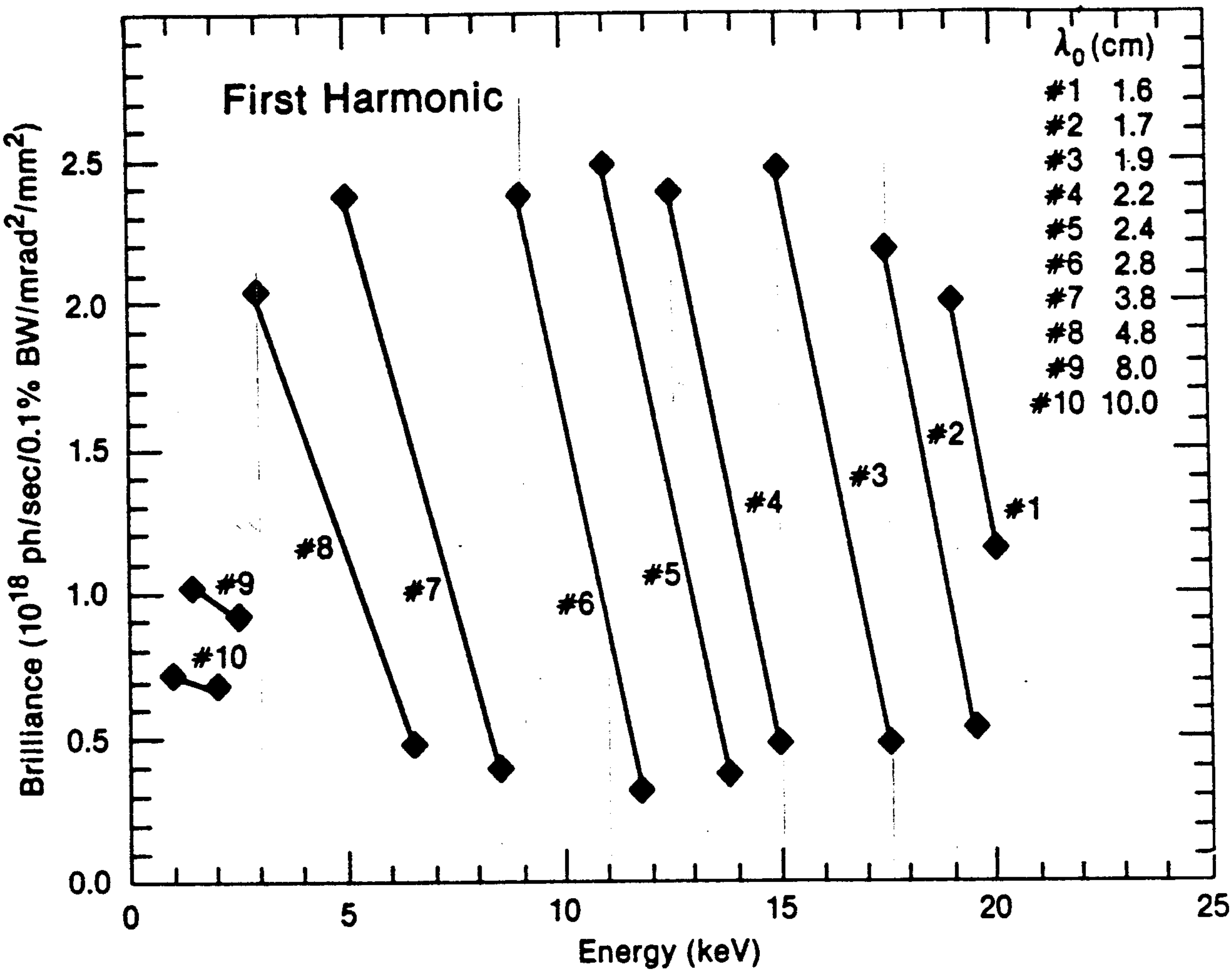


Figure 8 First-harmonic photon energies available with variable-gap undulators for different period lengths

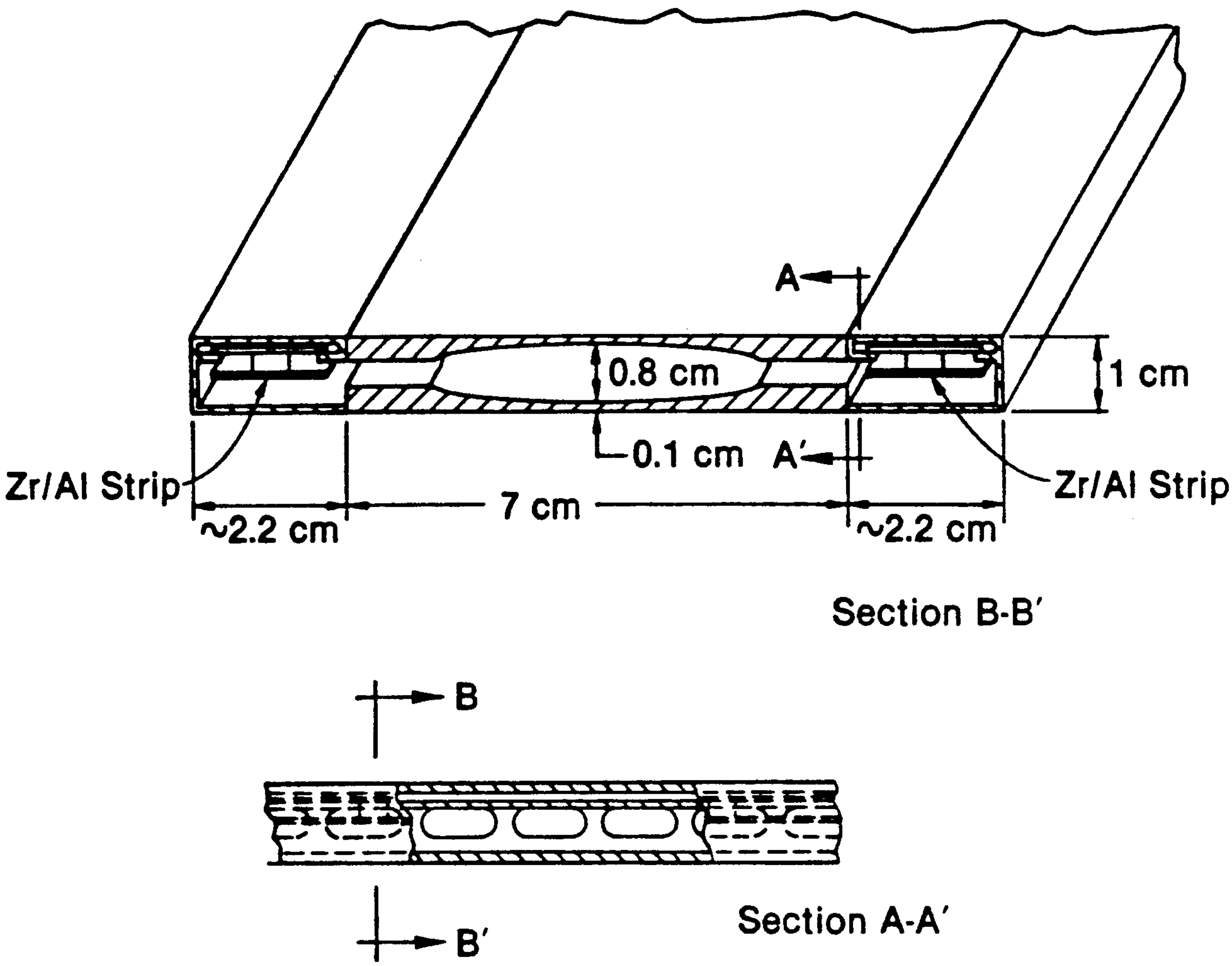


Figure 9 A rigid vacuum chamber for a 1.0-cm gap, 20-keV undulator

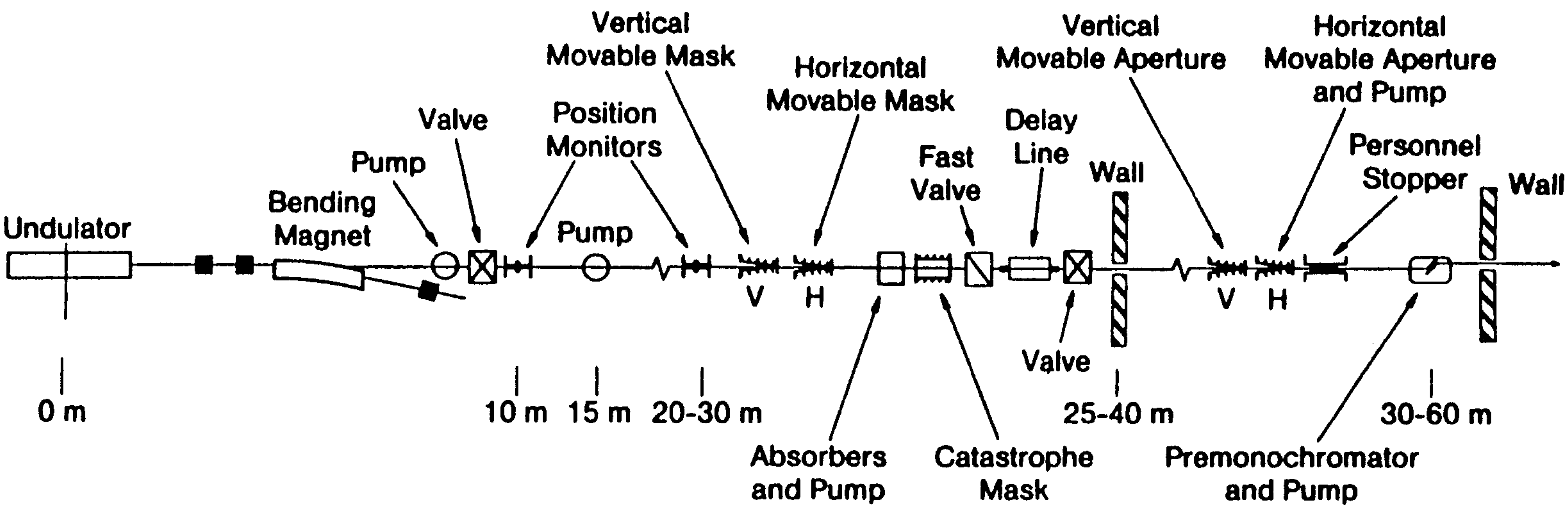


Figure 10 Layout of a generic front-end of a beam line

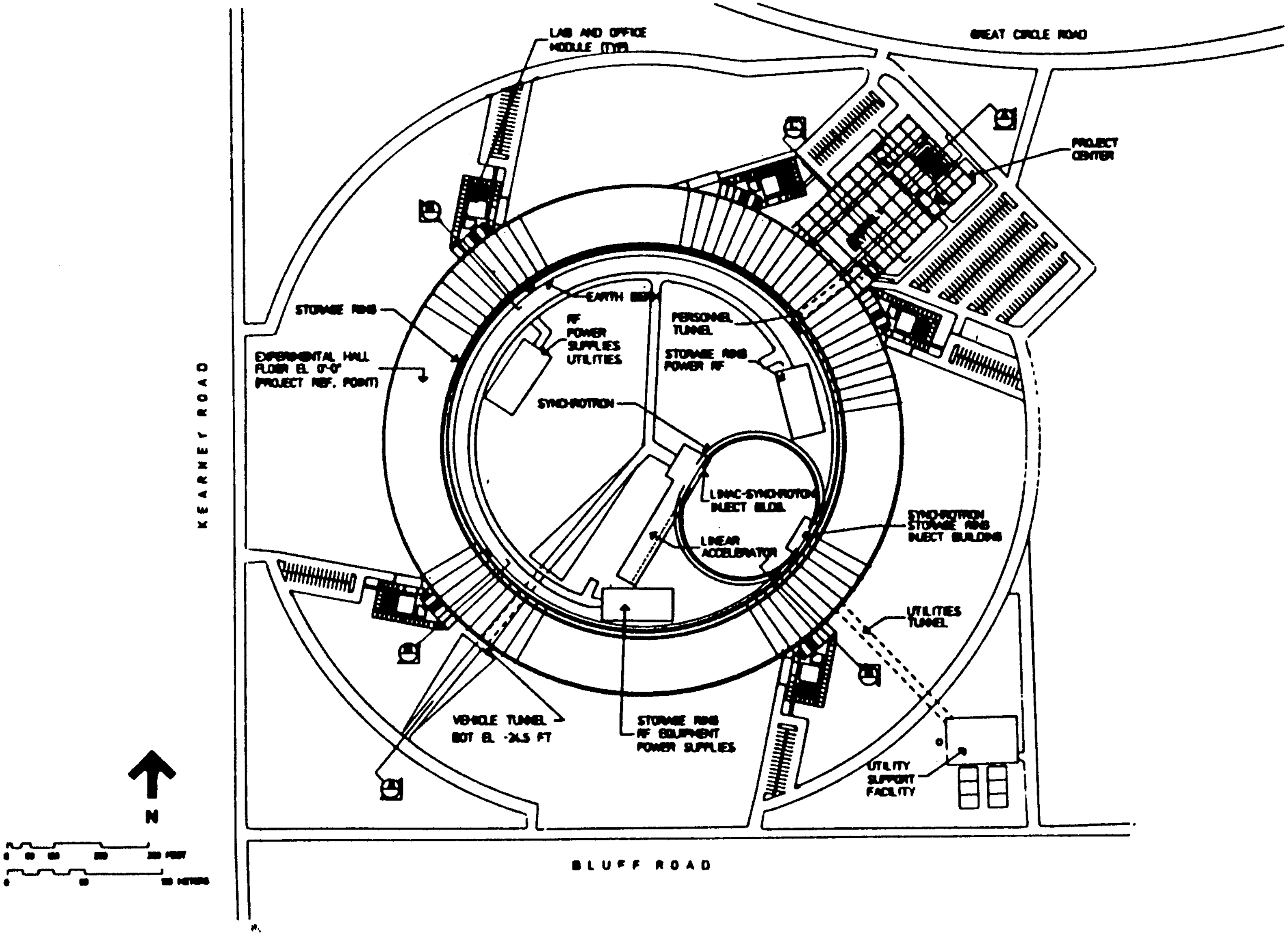


Figure 11 Overall building and site plan

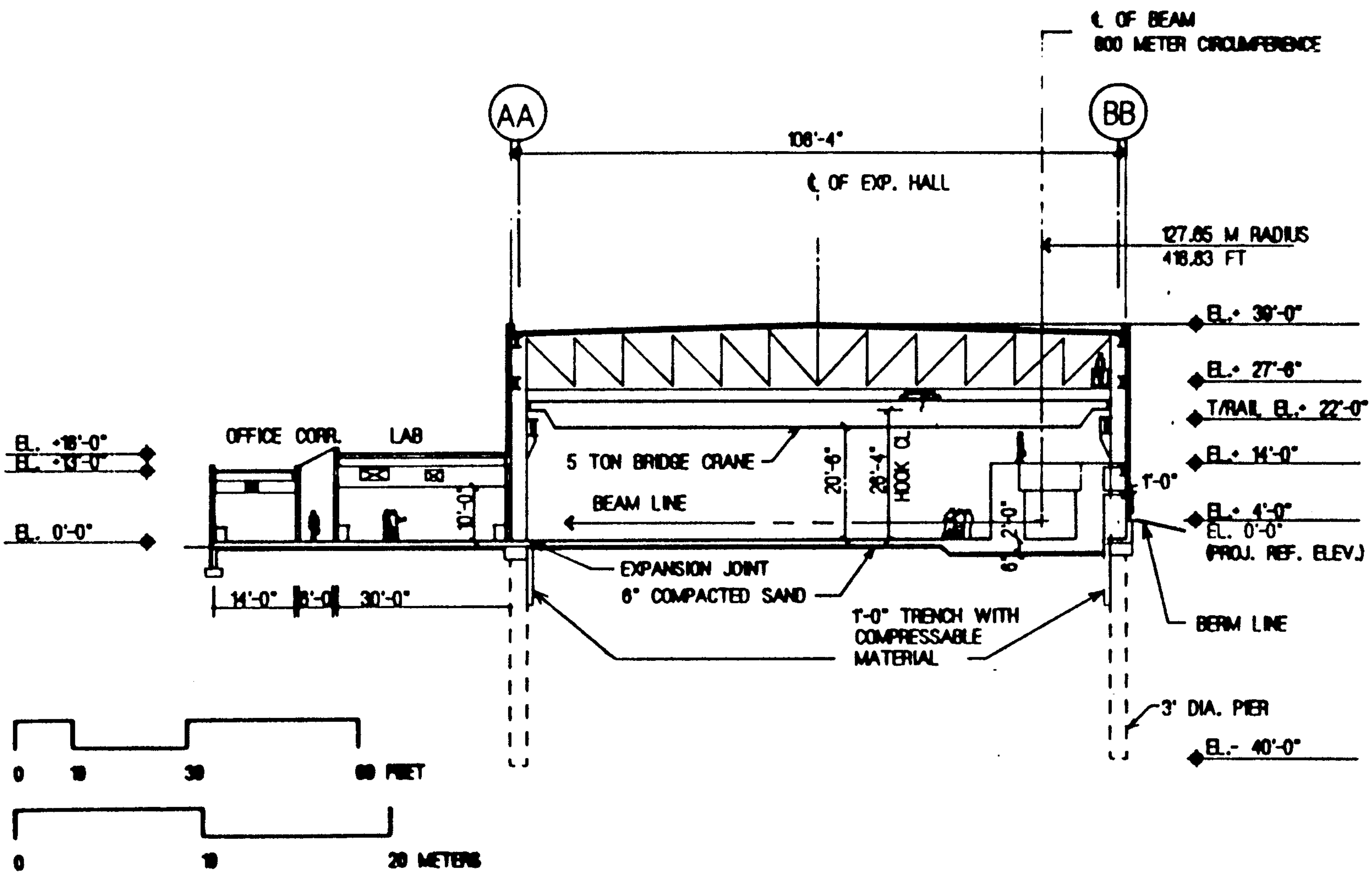


Figure 12 Cross-section of the experimental hall